5 Conclusions

This chapter presents conclusions that integrate findings outlined in the previous chapter. The findings providing primary basis for each conclusion are also reiterated. The conclusions are presented by study objectives.

5.1 Objective #1 – Characterize the weekend effect

Conclusion #1: ***The ozone weekend effect is real***

Careful statistical analyses of the available data demonstrate that the ozone weekend effect is a persistent reality and not just a transient condition or false impression.

Ozone measurements in some locations, primarily large metropolitan areas, are typically higher on weekends, particularly on Sunday, compared to weekdays. On the other hand, ambient concentrations of VOCs and NO_X, the major smog-forming pollutants, are typically lower on weekends almost everywhere, based on available air quality data and source-activity data, such as traffic counts.

Lower concentrations of ozone precursors on weekends seems reasonable because these emissions come from sources, such as cars, trucks, power plants, refineries, and factories. Intuition based on experiences and observations expects these sources to be less active overall on weekends compared to weekdays. Although it is likely that the major sources decrease in activity, some other activities, such as home maintenance, recreation, and shopping trips, may increase on weekends. On Saturday in some locations, for example, the total volume of mid-day traffic on freeways can be greater than on weekdays.

Characteristic differences between weekend ozone and Friday ozone are the following for four California air basins using data for 1996 – 1998:

- South Coast Air Basin – 22 ppb or 30% higher than Friday ozone
- San Francisco Bay Area Air Basin – 9 ppb or 25% higher than Friday ozone
- Sacramento Metropolitan area – 5 ppb or 8% higher than Friday ozone (not statistically significant)
- San Joaquin Valley Air Basin – 4 ppb or 6% higher than Friday ozone (not statistically significant)

Conclusion #2: ***Adverse health impacts from particulate matter are reduced on weekends as ambient concentrations of particulate matter tend to be lower on weekends compared to weekdays.***

Particulate matter (PM) in the air we breathe is a significant health concern. Exposure to particle pollution is linked to increases in the frequency and severity of asthma attacks and bronchitis. Even premature death in people with cardiac or respiratory disease has been attributed to elevated PM concentrations in the ambient air. Populations sensitive to particle pollution include people with respiratory or cardiac problems, children, and the elderly. Prolonged and repeated exposure can also have adverse impacts. All particles, irrespective of composition, can be harmful when inhaled, whether “coarse” (2.5 to 10 microns in aerodynamic diameter) or “fine” (less than 2.5 microns in aerodynamic diameter).

Analysis of PM concentrations indicates a general weekly pattern with the maximum occurring late in the workweek and the minimum occurring on weekends (especially Sunday); however, the pattern is not statistically significant in some locations.

Many different sources contribute to PM. Some sources emit PM directly (primary particles) while other sources emit pollutants that form secondary particles as they react in the atmosphere. Meteorological conditions can also affect PM concentrations strongly. Therefore, the cause(s) of day-of-week differences in PM concentrations are difficult to determine with confidence.

Ammonium nitrate – a secondary product of NO_X and ammonia emissions – is generally the largest contributor to PM2.5 concentrations during the winter at many urban sites in California and is also significant during the summer months in the SoCAB. Several studies indicate that ammonium nitrate can account for over half of the PM2.5 mass during episodes with elevated particle levels in California. Understanding how particulate ammonium nitrate is formed and how to effectively reduce it through controls on sources of NO_X, ammonia, or other pollutants (e.g., VOCs) influencing its formation is a critical component in the development of California’s PM2.5 program.

A factor contributing to increased PM2.5 concentrations in the winter is meteorology that favors the formation of secondary nitrate and sulfate. Cool temperatures, low wind speeds, low inversion layers, and high humidity are conditions that can lead to high concentrations of these particles. These meteorological conditions can also occur in marine layers during the summer. These meteorological conditions are also conducive for increased concentrations of primary particles, such as fine carbon particles, that contribute to the total mass of PM2.5.

The formation of secondary particles from precursors is a complex, nonlinear process, and one should not expect to see one-to-one relationships between precursor emissions and ambient concentrations of secondary PM.

Chemical reactions in the atmosphere convert NO_X emissions into very small nitrate particles. On weekends, activities that produce NO_X emissions appear to be substantially reduced. For example, heavy-duty diesel trucks are much less active on weekends than weekdays. Not surprisingly, average weekend concentrations for particulate nitrates tend to be lower than the average weekday concentrations.

Conclusion #3: ***Health risks associated with some important TACs (toxic air contaminants) are reduced on weekends as ambient concentrations tend to decrease on weekends compared to weekdays***

During the 1990s, ambient concentrations of two important carcinogens – benzene and 1,3-butadiene – decreased substantially. For example, between 1990 and 1998, the annual average concentration of benzene measured at Burbank, CA, declined by approximately 65 percent. The decrease in concentrations of 1,3-butadiene is also substantial, though somewhat smaller.

At the same time, ambient concentrations of these and other important TACs did not increase on weekends in areas where ozone concentrations do increase on weekends. In most cases, weekend concentrations were lower than weekday concentrations. This "negative" weekend effect appears to hold for primary TACs, such as benzene; 1,3-butadiene; and perchloroethylene, as well as secondary TACs, such as formaldehyde and acetaldehyde.

Particles contained in smoke from diesel engines have been identified as an important TAC. Ambient concentrations of elemental carbon (EC) include the particles from diesel smoke. Limited analysis of air quality data indicates that EC concentrations are probably lower on weekends compared to weekdays. This would be consistent with traffic data indicating that heavy-duty diesel trucks are much less active on weekends compared to weekdays.

5.2 Objective #2 – Examine the potential causes of the weekend effect

Conclusion #4: ***A coordinated research program including field studies, laboratory experiments, and modeling exercises is needed to provide a realistic hope of resolving the cause or causes of the ozone weekend effect.***

The cause or causes of the ozone weekend effect are difficult to resolve with existing data. As discussed under Conclusion #6, crucial gaps in the available data preclude a final judgement concerning the relative importance of the plausible causes of the ozone weekend effect.

The research needed to determine the cause(s) of the ozone weekend effect includes field studies, laboratory experiments, modeling exercises, and well-conducted analyses of all the resulting data. None of these areas of research will be sufficient by itself.

The recommendations in the following chapter outline a research program that should provide the crucial data needed to fill the important knowledge gaps. Although the necessary work will require a multi-year effort, reliable conclusions depend on significantly expanded and improved databases. The issues are reasonably clear, and the answers are within reach.

5.3 Objective #3 – Identify the plausible factors/causes of the weekend effect

Conclusion #5: ***Several processes may contribute to the ozone weekend effect. The relative importance of these processes cannot be fully resolved with presently available data from field studies, laboratory experiments, and modeling exercises.***

The analyses in this report provide a significantly better understanding of the ozone weekend effect. Still, the evidence falls short of determining the exact cause or causes of the ozone weekend effect. Of the seven hypotheses in Chapter 3, at least five are plausible and may explain a significant portion of the ozone weekend effect. Crucial gaps in the available data preclude a final judgement concerning the importance of each plausible cause of the ozone weekend effect. Based on the available evidence and the current state of knowledge regarding atmospheric processes, the staff summarizes in Table 5-1 its current assessment of the relative potential of the hypotheses (though not totally independent processes represented by them) to explain the ozone weekend effect.

Table 5-1. Characterization of the potential for the proposed hypotheses to explain the ozone weekend effect to a significant degree. Staff has concluded that none of the hypotheses are capable of solely explaining the weekend effect.

Hypothesis	Viable Explanation	Testability / Evidence	Likely Significance
Ozone Quenching	Yes	D / S	Major
NO_X Reduction	Yes	M / S	Major
NO_X Timing	Yes	M / M	Moderate
Carryover Aloft	Yes	L / L	Unknown
Surface Carryover	No	D / W	Minor
Aerosols & UV Radiation	Yes	L / W	Minor
Increased WE Emissions	No	L / W	Negligible

Testability: D – definitive test(s); M – multiple tests; L – limited tests
Evidence: S – strong; M – moderate; W – weak; L – limited

The research required to close the gaps in the data includes field studies, laboratory experiments, modeling exercises, and well-conducted analyses of all the resulting data. None of these areas of research would be sufficient by itself. Although the necessary work will require a multi-year effort, reliable determinations depend on significantly expanded and improved databases.

The data available today permit only a general assessment of the plausibility of the hypotheses in Chapter 3.

Conclusion #5a: ***The "NO_X-reduction" hypothesis is plausible but not proven.***

Although current measurement methods tend to underestimate VOC and overestimate NO_X and NO_2, the following observations are relevant to this conclusion:

- VOC/NO_X ratios measured near ground level in the SoCAB during daylight hours on all days of the week are generally in the "VOC-limited" range (less than 8 to 10).
- VOC/NO_X ratios during daylight hours on weekends are generally 10-20% higher on Saturdays and 20-40% higher on Sundays compared to weekdays.
- NO_2 to NO ratios on weekends are higher than on weekdays during daylight hours.

Limitations in the data pertinent to this conclusion are the following:

Directly measured VOC data are available for only a few locations in the SoCAB. An hourly database of accurate VOC measurements representing all parts of a region for all days of the week (with adequate replication) is not available anywhere in California, perhaps anywhere in the world.

The precision of air quality measurements is often too coarse to see significant changes in the VOC/NO_X ratio. Routine VOC measurements from the PAMS program may significantly underestimate the true VOC concentrations, while routine NO_X measurements systematically overestimate the true sum of NO and NO_2 due to artifacts included in the measurement. Therefore, the true VOC/NO_X ratios may be substantially higher (20-40% or more) than the estimated VOC/NO_X ratios based on ambient data.

For all days, ambient NO_X concentrations are usually under 60 ppb by mid-day and rarely exceed 60 ppb at any time on Sunday. Furthermore, NO_X concentrations decrease with time and distance from NO_X sources. Such conditions may significantly reduce the ozone-forming potential of VOCs as the air mass evolves toward the NO_X-limitation regime.

Accurate, artifact-free measurements of VOC species and NO_X species (NO, NO_2, and other important nitrogenous pollutants) are needed. Besides surface measurements, these data are needed at several altitudes above the ground to help separate the contributions of the "NO_X-reduction" hypothesis, the "NO_X-timing" hypothesis, and the "carryover aloft" hypothesis.

Conclusion #5b: The “NO_X-timing” hypothesis is plausible but not proven.

The following observations (with the earlier measurement caveats) are relevant to this conclusion:

- Measured VOC/NO_X ratios during daylight hours on weekdays and weekends are generally in the “VOC-limited” range (less than 8 to 10), but increase, becoming less “VOC-limited,” as the hours progress.

- NO_2 to NO ratios on weekends are higher than on weekdays, especially in the early daylight hours, indicating more active photochemistry.

- Ozone concentrations increase earlier and for more time on weekends than weekdays.

- NO_X concentrations on weekend mornings are typically 40-50% of the concentrations on weekday mornings. By the early afternoon, however, weekend NO_X concentrations are generally 60-80% of weekday levels, indicating that NO_X emissions are “catching up” to weekday levels. In fact, traffic data indicate that vehicular activity at mid-day is comparable, and, at some times and locations, higher than on weekdays. The slightly divergent air quality and traffic data could be indicating that the higher O_3 concentrations on the weekend than weekdays might more rapidly remove NO_X from the photochemical system. Thus, the lower NO_X concentrations at mid-day on weekends than weekdays could be indicative of faster NO_X removal rather than lower NO_X emissions.

- Due to dilution and chemical reactions, ambient NO_X concentrations decline before mid-day almost everywhere, especially on Sunday. The VOC/NO_X ratio estimate increases during the day and NO_X emissions are more likely to promote rather than inhibit ozone formation. Current VOC and NO_X measurements, with biases toward lower VOC/NO_X ratios, indicate that O_3 formation may or may not still be in the “VOC-limited” range at mid-day.

Limitations in the data pertinent to this conclusion are the following:

Additional field sampling and chemical analyses are needed, along with modeling to ascertain how different the photochemical state of the atmosphere is on weekends compared to weekdays.

Accurate, artifact-free measurements of VOC species and NO_X species (NO, $NO_{2,}$ and in three dimensions are needed to assess the contributions of the “NO_X-timing” hypothesis, as well as “NO_X-reduction” and “Carryover aloft” hypotheses.

Conclusion #5c: ***The "carryover near the surface" hypothesis is plausible but not likely to be an important factor.***

Carryover within the nighttime layer of cool air near the surface is probably not an important factor contributing to the ozone weekend effect. Traffic activity data on freeways in the South Coast Air Basin indicate greater activity on Friday and Saturday evenings. However, air quality data indicate that ambient concentrations of VOCs and NO_X at sunrise are similar on weekends compared to weekdays.

The following observations are relevant to this conclusion:

- Total traffic on Friday and Saturday nights is greater than the total traffic on other nights.
- Ambient concentrations of CO and NO_X during the nighttime hours on Friday and Saturday nights are similar to or higher than the nighttime concentrations on other days of the week.
- Ambient concentrations of CO and NO_X at sunrise on Saturday and Sunday are similar to or lower than the comparable concentrations on weekdays.

Limitations in the data pertinent to this conclusion are the following:

However, because VOC data have historically been limited in quantity and quality, analysis of better quality (e.g., better precision and accuracy) data is needed to confirm this for hydrocarbon concentrations. The fate of ozone precursor emissions during the night needs to be confirmed whether or not the reaction products can become photochemically active when the sun rises.

Conclusion #5d: ***The "carryover aloft" hypothesis is plausible but not proven.***

The following observations are relevant to this conclusion:

- Based on measurements with LIDAR, airplanes, and balloons, reservoirs of ozone and ozone precursors appear to occur aloft frequently, perhaps routinely, in the South Coast Air Basin.
- Reservoirs aloft are frequently substantial, some being thousands of feet thick beginning a few hundred feet above the surface, and containing 60 – 140 ppb or more of ozone.
- Measurements aloft indicate that photochemistry is frequently NO_X-limited or NO_X-sensitive. Concurrent surface measurements usually indicate the reverse.
- LIDAR data and three-dimensional dispersion models indicate that pollutants aloft generally begin mixing into the nocturnal boundary layer three or more hours before the ozone maximum occurs.

- Some LIDAR data indicate that pollutants sequestered aloft may generate additional ozone before mixing begins with fresh emissions from the surface.

Limitations in the data pertinent to this conclusion are the following:

Measurements of air quality aloft are typically made during special field studies on days when high ozone concentrations are anticipated. Air quality measurements aloft, especially of ozone and ozone precursors, are needed on many more days, including non-episode days. These measurements are needed for weekday-weekend transitions (Fri. to Sat. to Sun. to Mon.). In addition, photochemical modeling that replicates the observed carryover phenomena is needed to evaluate the influence of carryover aloft on the ozone weekend effect.

Accurate, artifact-free measurements of VOCs and NO_X in three dimensions are needed to assess the contributions of the "Carryover aloft" hypothesis, as well as the "NO_X-reduction" and "NO_X-timing" hypotheses.

Conclusion #5e: ***The "increased weekend emissions" hypothesis is not plausible.***

According to the increased weekend emissions hypothesis, total smog-forming emissions increase on weekends. A few observations are consistent with this hypothesis, but the vast majority of air quality data does not support it.

The following observations are relevant to this conclusion:

- The Lynwood monitoring site represents an urban source region for VOCs and NO_X. This site records the highest mid-day levels of CO on Saturdays (10 a.m. to 3 p.m.). However, this observation should not be generalized in support of the increased weekend emissions hypothesis for two reasons. First, the highest ozone day in the SoCAB is Sunday, rather than Saturday. On Sunday, Lynwood CO levels do not exceed mid-week levels between 6 a.m. and 8 p.m. Second, no location other than Lynwood shows a similar pattern.

- Daily total vehicle counts at some Weigh-in-Motion stations in the SoCAB are higher on some weekend days than on weekdays. However, these stations tend to be at peripheral locations affected by traffic leaving and entering the basin.

- Hourly vehicle counts from 11 a.m. through 3 p.m. are often higher on Saturday than on weekdays. However, mid-day vehicle counts on Sundays at almost all locations are lower than on weekdays, and Sundays have the highest ozone everywhere in the SoCAB.

- Air quality data at most locations do not support the Increased Weekend Emissions Hypothesis. With the exception of CO on Saturdays at the

Lynwood and El Toro monitoring sites, ambient measurements of CO (partial hydrocarbon surrogate) and NO_X are lower on weekends compared to weekdays for all daylight hours.

Conclusion #5f: ***The "aerosol and UV radiation" hypothesis is plausible but not proven.***

According to the "aerosol and UV radiation" hypothesis, concentrations of particles that absorb ultraviolet sunlight are lower on weekends compared to weekdays. Therefore, more ultraviolet sunlight is theoretically available to drive ozone-forming reactions in the atmosphere, and this causes ozone concentrations on weekends to be greater compared to weekdays.

At this time, only a few theoretical exercises and a limited store of field measurements are available to test this hypothesis. Although these (initial) efforts indicate it might not be a major factor in the ozone wekend effect, staff includes recommendations in this report to acquire the data needed to evaluate this hypothesis more fully.

Conclusion #5g: ***The "ozone quenching" hypothesis is plausible but not the sole factor.***

Ozone quenching by fresh NO emissions has always occurred and with the early morning differences in NO emissions from weekdays to weekends is a logical factor in why ozone concentrations are higher on weekend mornings than on weekday mornings. Diurnal and day-of-week profiles of oxidant (O_3 + NO_2) levels suggest that a large part of the ozone weekend effect is due to ozone quenching. However, it does not directly explain all of the weekend effect. Furthermore, as NO emissions decline, one would anticipate that the amount of ozone quenching would also decline and the difference between weekday and weekend ozone concentrations would decline. However, the ozone weekend effect now is observed at more monitoring sites than ever before. One potential explanation is the increased urbanization around the monitoring network, which has remained quite stable in the SoCAB over the years. As the metropolitan area becomes more urbanized (denser development and traffic activity increases), the ozone quenching effect becomes more noticeable at many monitoring sites and the weekend effect increases with time.

5.4 Objective #4 – Evaluate control strategy implications from the weekend effect

Conclusion #6: ***A combination of VOC and NO_X reductions has been highly successful at reducing ambient ozone levels on all days of the week everywhere in the basin for more than 20 years in the South Coast Air Basin. Nevertheless, the ozone weekend effect occurs throughout the SoCAB.***

By the late 1990s, the ozone weekend effect was observed at all locations in the South Coast Air Basin for which data were analyzed (see Section 1.4 of the TSD).

From the mid-1970s into the 21st century, the ozone control strategy implemented in the SoCAB included reductions of both VOC emissions and NO_X emissions. Early NO_X reductions were achieved by statewide controls on emissions from motor vehicles combined with local controls on emissions from industrial sources, such as cement kilns and power plants.

While both VOC and NO_X emissions decreased substantially, ambient ozone levels also declined substantially on all days of the week at all locations in the basin (See Section 1.1 of the TSD).

Conclusion #7: *The ozone weekend effect does not invalidate NO_X reductions as an important ozone control strategy. In addition, NO_X reductions are almost certainly beneficial in reducing concentrations of some other pollutants, such as, nitrogen dioxide and PM-nitrates.*

Uncertainties remain as to the causes of the ozone weekend effect. The ozone weekend effect is not a simple phenomenon, and may be caused by any of several processes operating separately but more likely in concert. Given all the concurrent variations in the nature, timing, and distribution of emissions when transitioning from a weekday pattern to a weekend pattern of emissions, staff has serious doubts about the relevance of the weekend effect to the long-term control strategy. The causes of the ozone weekend effect might persist during periods when the VOC and NO_X reductions cause ozone concentrations to improve at all sites in the basin on all days of the week. The trend data indicate that the ozone weekend effect is a temporary day-of-week perturbation within the declining ozone levels. Ozone is declining on all days of the week; however, the rate of decline is slower on weekends than on weekdays. Until it is apparent that the weekend ozone levels, which now represent the peak levels for the basin, are not responding to the dual precursor control strategy, NO_X reductions remain a rational and valid element of ozone control strategies.

From a regional and global perspective, NO_X reductions are necessary to reduce the impacts of transport and increasing background concentrations. As background levels of ozone increase, the margin between them and the health-based standards decrease. The net impact would be to increase the amount of local emission controls necessary to comply with the ambient air quality standards. This increasing background effect would have even greater control implications for attaining the 8-hour standard than the 1-hour standards because the 8-hour standard is much lower and closer to background levels. Furthermore, allowing background levels of ozone to increase would have significant environmental implications because ozone is not only a powerful oxidant, it is also a global warming gas.

In addition, NO_X reductions affect pollutants other than ozone. Ambient concentrations of nitric acid (HNO_3), PM-nitrate, and nitrogen dioxide (NO_2) are affected by NO_X emissions. Recent research on health effects indicates that exposure to air pollutants for multiple years lowers the growth rate of lungs in children. The pollutants most strongly associated with this effect include NO_2, particulate matter, and nitric acid. The federal and California ambient air quality standard for NO_2 were attained in the early and mid-1990s in the South Coast Air Basin.

Reductions in NO_X emissions can also reduce the mass of nitrate particles in the air. Particulate nitrates often make up a large fraction of the total mass of PM2.5, which can penetrate deeply into lungs. Most particulate nitrates are formed, in part, from gaseous NO_X emissions through photochemical processes.

Because multiple pollutants are affected by NO_X reductions, they are often considered together, rather than separately, when developing pollution control plans.

Conclusion #8: ***The ozone weekend effect is not representative of what is expected to occur with a dual precursor emissions reduction program.***

If the weekend effect is used to represent the effect of a control strategy, the changes in emissions must be similar in all important respects. However, changes in emissions from weekday to weekend include differences in the composition, timing, and location of emission sources. Control strategies often have little impact on some of these aspects of emission sources. Given the demonstrable differences, the WE effect is not a reliable basis for designing an O_3 control strategy to protect public health.

First, emission changes associated with the weekend effect in the Los Angeles area include greater reductions in NO_X (perhaps twice as much as VOC due to reduced activity of heavy-duty diesel trucks) while historical emission trends show VOC reductions were about twice as great as NO_X reductions. Projections of emissions from now to 2010 show approximately equal NO_X and VOC reductions. This difference between the relative reductions of the O_3 precursors on the weekend and over the years would likely influence the photochemistry of the air mixture by changing the VOC/NO_X ratio and causing a different photochemical regime for O_3 formation.

Second, temporal changes on the weekend differ from those associated with most control measures. Control measures reduce emissions over the time those emission sources are active. Temporal changes in emissions associated with the transition from weekday to weekend include: 1) the transition from bi-modal (morning and evening) traffic peaks (i.e., WD commute periods) to a uni-modal (mid-day) peak; and 2) more evening activity on Friday and Saturday. Hence, much of the emissions go into a different physical and chemical environment on the weekend than on a weekday.

Third, the spatial distribution of emissions is different on weekdays than on weekends. Traffic data indicate a shift in activity from the urban business zones toward residential and recreational areas. Furthermore, the activity of heavy-duty vehicles is likely to decline more in the central basin than near the entry points to the basin. Emission control measures tend to reduce emissions where they occur rather than redistributing them.

Fourth, emissions and meteorology on any given day influence the atmospheric loading of ozone, ozone precursors, and reaction products that carry over to the following day. In other words, air quality "today" depends, in part, on pollutants that persist from "yesterday". Daily emissions of ozone precursors, particularly NO_X, decrease from Friday to Saturday to Sunday and increase again on Monday. Because the potential for carryover is proportional to daily emissions, the fresh emissions on a Saturday and Sunday occur into an environment influenced by the higher emissions of the preceding day. Similarly, the emissions on Monday occur in a context established by the lower emissions on Sunday. This may explain why average ozone levels on Mondays have typically been the lowest of all the weekdays. Future NO_X reductions associated with a control program would affect emissions on all days continuously rather than intermittently (i.e., every 7^{th} day). In Los Angeles, this carryover occurs in the large reservoir of ozone and ozone precursors extending hundreds of meters above the surface layer, and is not captured by routine surface-based measurements.

For these reasons, the ozone weekend effect has limited and uncertain application toward predicting the impacts of future emission controls.